PHENIX Highlights I: Propagation of Partons in a Colored Medium

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Abstract. In this contribution I present recent results from the PHENIX collaboration, with a particular emphasis on measurements relating to the propagation of partons in a colored medium.

1. Introduction

RHIC has enjoyed a history of exciting discoveries. The fact that the matter that we have created is dense is evidenced by measured R_{AA} for identified and unidentified hadrons. That the matter is strongly interacting is demonstrated by the nonzero elliptic flow of non-photonic electrons. Two-particle correlations show a modification of the away-side correlation function, indicating interactions between the scattered parton and the colored medium. Charmonium suppression has been observed, but a detailed picture of the interplay between suppression and regeneration has yet to emerge.

All of these observations have been a significant part of previous Quark Matter conferences, and yet much work still remains to extract detailed, quantitative information. In this contribution I will present new PHENIX measurements related to the propagation of partons in a colored medium and attempt to use this information to push back the boundaries of our understanding of hot, dense QCD matter. This picture, of course, is by no means complete and new measurements from PHENIX related to photons, hadronization and thermalization will be discussed in a second contribution to this conference by Matthias Perdekamp.

2. Light Quark/Gluon Energy Loss

The observation of the suppression of hadrons at high transverse momentum is one of the keystone observations at RHIC. These measurements have now been made out to very high transverse momentum (out to $p_T \sim 20$ GeV/c for π^0 mesons) and in both heavy and light colliding systems. Models of energy loss that focus on radiative processes as the

† For the full list of PHENIX authors and acknowledgements, see appendix 'Collaborations' of this volume.

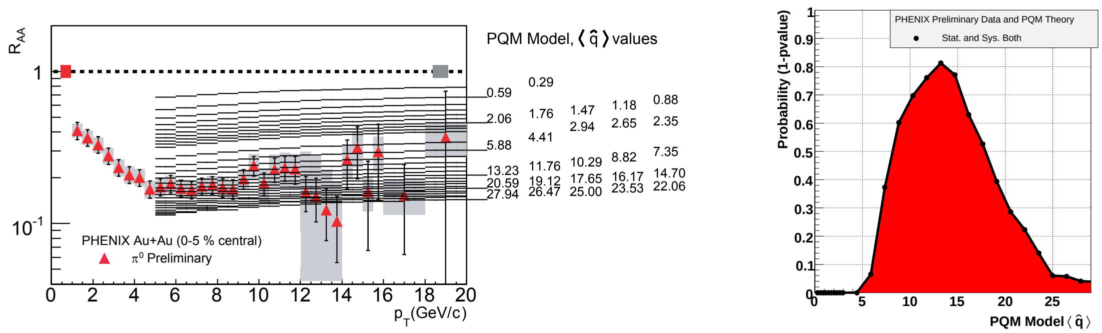

Figure 1. A detailed comparison between PHENIX preliminary data on the R$_{AA}$ of π^0 mesons in central Au+Au collisions and calculations in the PQM model. See text for details.

dominant mechanism have had notable success in describing the current RHIC datasets, typically in terms of a transport coefficient $<\hat{q}>$ or the rapidity density of gluons in the medium dN_G/dy. However, the fact that measured R$_{AA}$ values are so small suggest that in a detailed, quantitative comparison between theory and experiment it will be difficult to extract a single value of these parameters, but rather a range of parameters that are consistent with the experimental data within certain criteria.

Figure 1 shows a comparison between one particular model calculation of R$_{AA}$ resulting from radiative energy loss and the PHENIX data for π^0 mesons in central Au+Au collisions. Each curve in the plot on the left corresponds to a value of $<\hat{q}>$ [1]. Performing a χ^2 comparison between the theory curve and the data, including statistical and systematic errors on the experimental points, results in the probability distribution shown on the right [2]. Such an analysis allows us to make a quantitive statement regarding the agreement of the model with the PHENIX data. For example, the range of the parameter $<\hat{q}>$ that has a greater than 10% probability of being the correct description of the PHENIX data is given by $6 \leq <\hat{q}> \leq 24$ GeV^2/fm. It is important to note that such a statement does not include any theoretical uncertainties that may also contribute to the range of allowed $<\hat{q}>$ values. While I show results here for a comparison to the PQM model, such an analysis can be performed for any theoretical model with detailed numerical predictions.

Another way to gain additional information about the energy loss of light quarks and gluons is to vary the collision geometry. When we divide collisions into centrality classes, we implicitly vary the range of pathlengths traversed by the partons as they exit the medium. In addition, we can also vary the angle of emission of the partons with respect to the collision reaction plane and obtain fine control over the thickness of the nuclear matter (L_ϵ) as a function of reaction plane angle, which can be calculated in a simple Glauber model.

Figure 2 shows PHENIX data on the R$_{AA}$ value for π^0 mesons in two different p_T ranges as a function of the matter thickness L_ϵ. Different centrality ranges are shown combined on the plots, and the combination of centrality and reaction plane emission

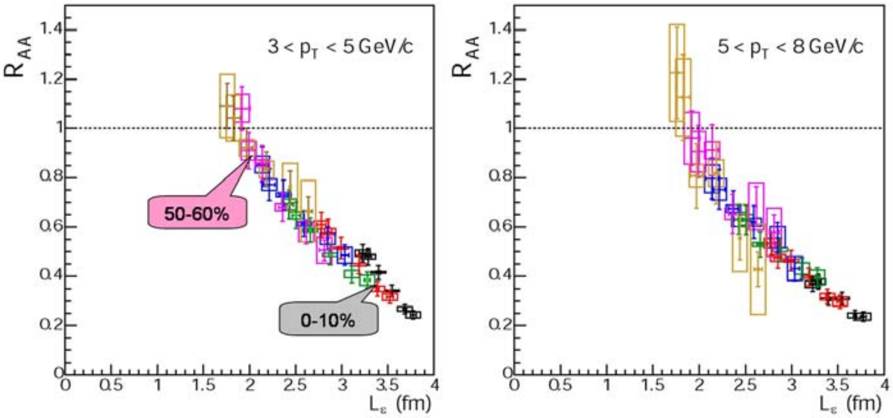

Figure 2. Dependence of the R_{AA} value for π^0 mesons as a function of the parameter L_ϵ.

angles leads to a smooth evolution of the data as a function of L_ϵ. What is striking is that R_{AA} values rise to one for small values of the matter thickness, $L_\epsilon < 2$ fm [3, 4]. This data provides strong, detailed constraints on energy loss models and their combination with collision geometry to yield the experimentally observed patterns of suppression.

3. Particle Correlations

Measurements of two-particle correlations at RHIC and at the SPS have shown a striking modification of both the shape and strength of the away-side correlation function for intermediate trigger momenta ($2.5 < p_T < 4.0$ GeV/c) and low associated particle momenta ($1.0 < p_T < 2.5$ GeV/c) [6, 5]. These modifications are due to interactions of the parton with the intervening matter, ranging from simple scattering to bulk phenomena such as Mach cones and shock waves.

Improvements in the understanding of systematics in the PHENIX data now permit a detailed, quantitative study of the shape of the away-side correlation function as a function of centrality, center-of-mass energy, and colliding system. We have chosen to characterize the correlation function shapes in two ways. First, we describe the shape using the kurtosis, which is formed from the second and fourth central moments around $\Delta\phi = \pi$:

$$\mu_n =< (\Delta\phi - \pi)^n > \quad (1)$$

where n=2,4. In this formulation the rms of the distribution is given by $\sqrt{\mu_2}$ and the kurtosis by $\mu_4/{\mu_2}^2$. Simply put, the kurtosis measures a deviation of the distribution from a Gaussian shape, where a kurtosis of three indicates a pure Gaussian.

In the second case we use a phenomenological splitting parameter extracted by fitting the correlation function to a combination of Gaussian functions $G(\Delta\phi)$:

$$J(\Delta\phi) = G(\Delta\phi) + G(\Delta\phi - \pi + D) + G(\Delta\phi - \pi - D) \quad (2)$$

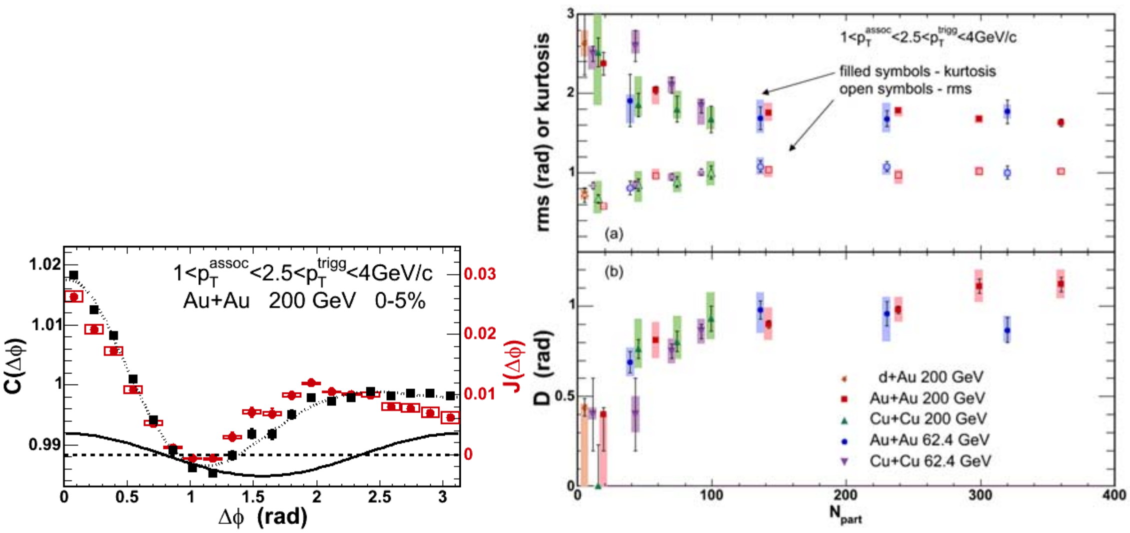

Figure 3. On the left is shown a two-particle correlation function for central Au+Au collisions, with the raw correlation function and v_2 contributions in black (left scale) and the extracted jet function in grey (right scale). The right panel shows the characterization of the shape of the away-side correlation function through the kurtosis, rms and splitting parameter D.

where the first term represents the near-side peak, while the second and third terms represent the away-side peak. The splitting parameter D is roughly the width of the dip or flat region in the away-side correlation function.

As can be seen in Figure 3, all three characterizations of the away-side correlation follow the same trend line as a function of centrality, collision species and collision energy. This behavior is quite striking, indicating that the away-side suppression is only a function of N_{part}, or the amount of nuclear overlap in the initial stage of the collision. We have also examined the dependence of these parameters on the transverse momentum of the associated hadrons and found little dependence. These observations are consistent with shock wave or Mach cone models, but pose challenges for simple Cherenkov gluon radiation [7, 8].

In order to be able to distinguish medium excitation from, for example, a large event-by-event scattering of the jet axis, it is necessary to move to a three-particle correlation technique. PHENIX has chosen to characterize three particle correlations through the use of two angles, as shown in Figure 4. The angle $\Delta\theta^*$ measures the hemisphere of the correlation relative to the trigger particle momentum, while the angle $\Delta\phi^*$ measures the azimuthal angle.

The resulting three-particle correlation function is shown in Figure 4. It is important to note that this correlation function as generated includes the effect of the PHENIX acceptance. After applying corrections for elliptic flow contributions and comparing with Monte Carlo simulations of various jet modification scenarios, it appears that the PHENIX measurements are most consistent with the excitation of a Mach cone in the medium and not consistent with a "bent" or "normal" (back-to-back) jet

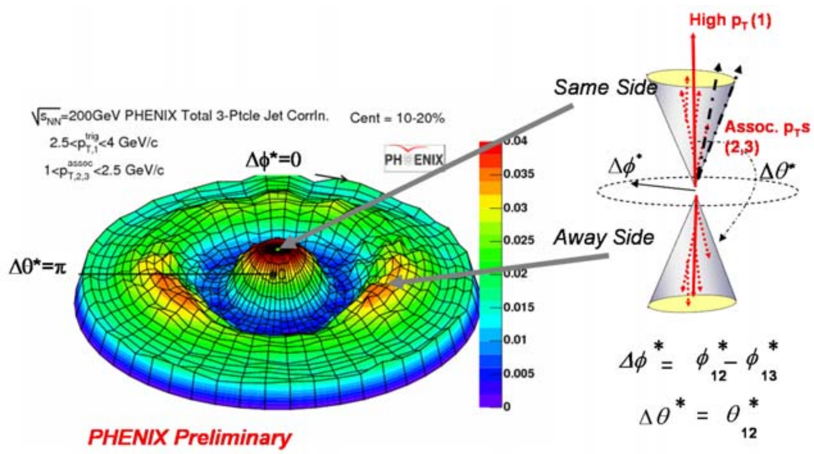

Figure 4. The PHENIX three-particle correlation function in the PHENIX acceptance, with a diagrammatic explanation of the angular variables. The vertical scale is normalized by the number of trigger particles. This correlation function is not corrected for the elliptic flow contributions.

hypothesis [9].

Direct photon-hadron correlations promise to provide an energy calibration that will allow quantitative study of the energy loss of the jet recoiling opposite the direct photon. PHENIX has begun the study of these processes using the correlation function technique [10]. The PHENIX measurements in p+p collisions are in good qualitative agreement with pythia calculations, and initial measurements in Au+Au collisions indicate a suppression of correlation strength relative to p+p collisions. These measurements are clearly in their infancy, but such proof-of-principle results offer great promise for the future.

4. J/Ψ Production

The suppression of charmonium in heavy-ion collisions has long been proposed as a signal for the onset of deconfinement in QCD matter [13]. J/Ψ suppression has been observed at both the SPS [14, 15] and at RHIC, with a remarkably similar pattern of suppression at midrapidity as a function of the number of participating nucleons [12]. This is quite striking, as it is expected that cold matter suppression is larger at SPS energies, while hot matter suppression and recombination are more important at RHIC. It remains to be explained how a conspiracy of competing effects can yield results at RHIC that are similar to those at the SPS.

PHENIX has made new baseline measurements of J/Ψ production in p+p collisions, including p_T spectra and rapidity distributions [16, 17, 18]. These measurements will provide important baselines for detailed comparisons with heavy-ion collisions.

Figure 5 shows the R_{AA} for J/Ψ production in Au+Au collisions in two rapidity regions. It is interesting to note that the suppression is larger in the higher rapidity range, which indicates that the suppression of the J/Ψ is not a trivial function of the

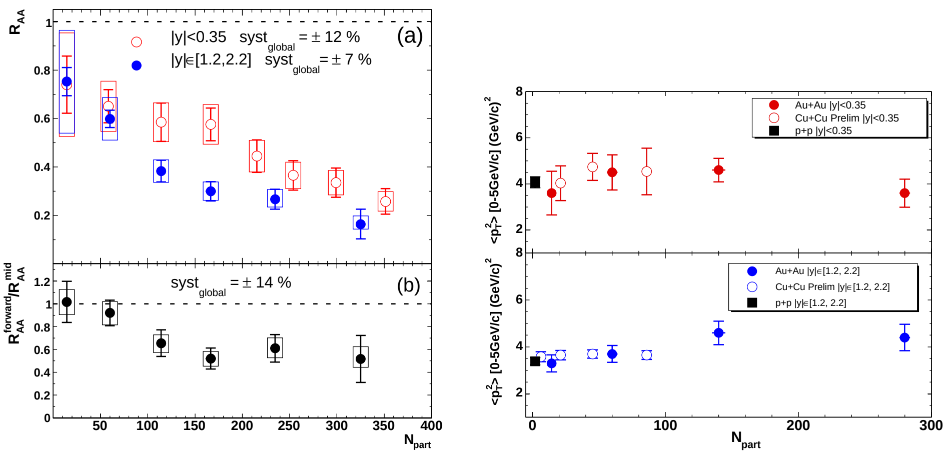

Figure 5. The left panel shows the R_{AA} for J/Ψ production in Au+Au collisions at central and forward rapidities, along with the ratio in the bottom of the panel. The right panel shows PHENIX measurements of the $< p_T{}^2 >$ for p+p, Cu+Cu and Au+Au collisions.

local particle density and enhancement mechanisms may be contributing. Also in Figure 5 is the $< p_T{}^2 >$ of the J/Ψ as a function of centrality for p+p, Cu+Cu and Au+Au collisions, evaluated by integrating the data for $p_T < 5$ GeV/c. It is interesting to note that $< p_T{}^2 >$ is essentially flat in both rapidity ranges, which places a constraint on the contribution of recombination to the total J/Ψ yield [12].

5. Heavy Flavor

As mentioned in the introduction, the observation that charm couples to the medium provides key insight into the matter created at RHIC. PHENIX has made new measurements of the elliptic flow and energy loss of charm that serve to quantify the strength of the coupling and further elucidate the properties of QCD matter.

PHENIX measures charm indirectly, through the measurement of non-photonic electrons, which is obtained by subtracting photon conversion contributions from an inclusive spectra. This is done in two ways, a cocktail method using measured and scaled particle production, and a converter method which increases the material in the PHENIX acceptance to provide a baseline for subtracting photon conversions [11]. PHENIX measurements of non-photonic electrons in p+p collisions, an important baseline, are shown in Figure 6 compared to a fixed order next-to-leading log (FONLL) calculation. The PHENIX data is in agreement with the FONLL calculation within the theoretical uncertainty bands, and this agreement is consistent with comparisons made at higher energies [19].

PHENIX has also measured heavy flavor via non-photonic electrons in Au+Au collisions, as shown in Figure 7 as a function of collision centrality [20]. In the left-hand panel of Figure 7 the FONLL calculation has been scaled up to match exactly the p+p data, and then scaled by the number of binary collisions in each centrality

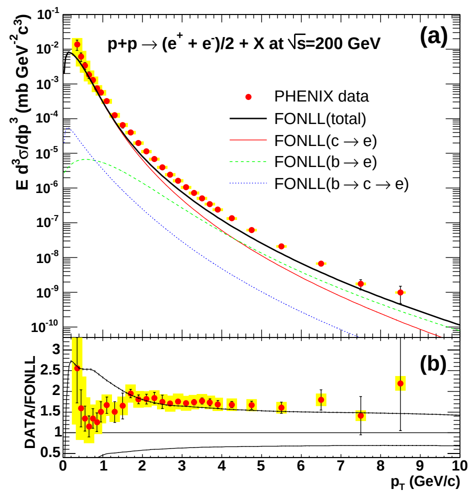

Figure 6. PHENIX measurements of non-photonic electrons in p+p collisions compared to FONLL calculations.

bin and overlaid on the Au+Au data. This comparison makes it evident that at higher centrality a suppression develops in the Au+Au data at large transverse momentum. The right-hand panel shows the R_{AA} for heavy flavor in two different p_T ranges as a function of centrality, compared to the π^0 suppression data. At low p_T there is little or no suppression of heavy flavor, while at high p_T the suppression pattern is similar to that for light quarks and gluons.

A significant challenge can be made to models of energy loss and elliptic flow of heavy flavor by demanding simultaneous consistency with data [21]. An example of this is shown in Figure 8, where the non-photonic electron R_{AA} shown compared to simultaneous predictions from theoretical models. Models that include only radiative energy loss fail to reproduce ${v_2}^{HF}$, while the heavy quark transport models show a reasonable agreement with both R_{AA} and ${v_2}^{HF}$. This implies a short relaxation time and/or a small diffusion coefficient for heavy flavor in the QCD medium.

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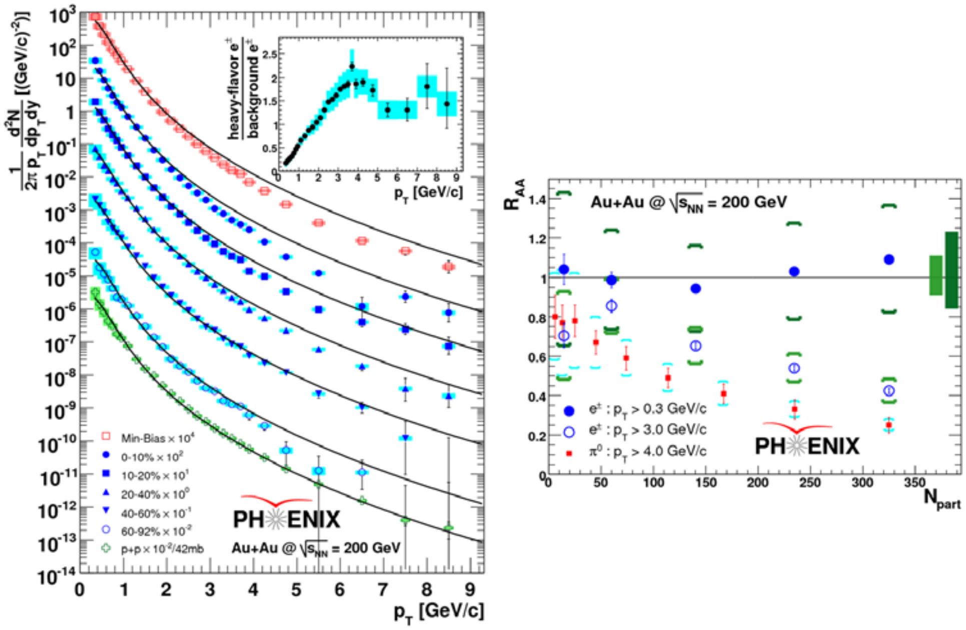

Figure 7. The left panel shows the invariant multiplicity of non-photonic electrons in different centrality ranges as measured in Au+Au collisions, compared to the FONLL prediction. The right panel shows the R$_{AA}$ for non-photonic electrons in different p_T ranges. The boxes at R$_{AA}$ = 1 show the relative uncertainty in each p_T range from the p+p reference.

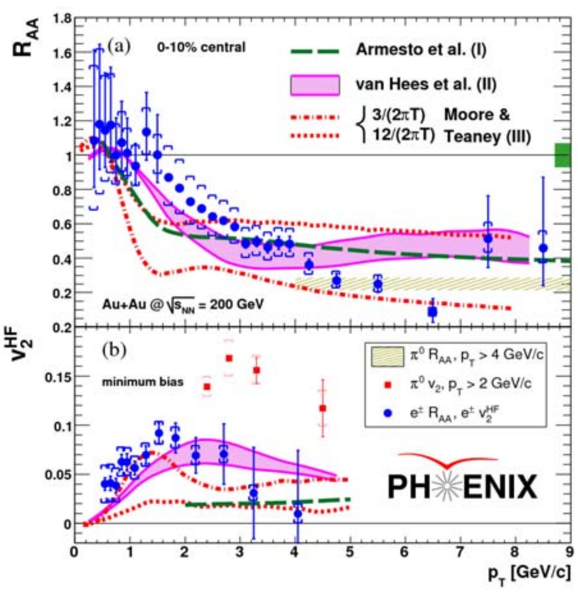

Figure 8. Simultaneous model comparisons for the R$_{AA}$ and v_2 of heavy flavor [22, 23, 24]. The systematic uncertainty in R$_{AA}$ due to collision scaling is shown as the box at R$_{AA}$ = 1.

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